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DEVELOPMENT OF A C-BAND PHASED ARRAY CROSSED-FIELD AMPLIFIER

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1.0 INTRODUCTION AND ABSTRACT

The purpose of this program is to develop a C-band phased array crossed-field amplifier to the specifications of Exhibit A of the contract, which are summarized in Figure 1. The tube is a broad band C-band amplifier with a high peak and average power capability which is to be dc operated with control electrode turn off. The amplifier is to be packaged with a 9" maximum diameter shielded permanent magnet structure.

The design and development of this tube are based upon the results which were obtained on a program conducted under Contract AF 30(602)-3633, where a 100 kw peak power output broad band, dc operated amplifier was developed. The results of that program have served as the basis for the present C-band effort. A particularly significant result of the X-band work was the development of a new slow wave structure for broad band forward wave amplifiers. This new structure, the helix coupled vane circuit (HCV), has demonstrated bandwidths in excess of the present 10% requirement. One of the important aspects of the program will be the examination of several variations of this circuit to arrive at an optimum design in terms of bandwidth, gain, efficiency, and power capability.

Two versions of the helix coupled vane circuit have been studied in cold test and are identified as Type A and Type B circuits. Work with the Type A circuit has advanced into the hot test stage. One hot test vehicle has been evaluated and a second vehicle is nearing completion. Matching studies on the Type A circuit have resulted in a very good match over approximately 1000 MHz and work is continuing on the match of the Type B circuit.

The essential elements of the electrical and mechanical design of the first tube were proven with the successful assembly and operation of the first test vehicle. Early hot tests were devoted to characterization of the slow wave circuit performance and the establishment of the correct interelectrode geometry. Tests made on these vehicles

Center frequency	5.65 GHz
Instantaneous bandwidth (1 db)	500 MHz
Peak power output	1 Mw
Average power output	10 kw
Gain	13 db
Cathode voltage	-25 kv max
Control electrode mu	3 min
Efficiency	
Minimum	40%
Average	50%

FIGURE 1 TARGET PERFORMANCE SPECIFICATIONS FOR C-BAND PHASED ARRAY CROSSED-FIELD AMPLIFIER

are pulsed and later test vehicles which are planned will incorporate control electrode structures for operation from a dc source. The second test vehicle will have a control electrode.

The cathode material study program was concluded with the determination of a cathode material which was demonstrated to have adequate properties for use in our first experimental vehicles. Additional tests concerning cathode materials will be deferred until such time as clear indications of cathode problems appear later during our hot test program.

All elements of the final test set are on hand with the exception of a high power water load which is on order and a high voltage dc power supply which is due at the end of October. An interim dc power supply has been allocated for program use in the meantime and will be capable of operating the amplifiers to at least half their rated average power.

Preliminary magnetic circuit evaluations have been made. The first choice of magnet structure was found inadequate with respect to magnet cross-sectional area. A new magnet design is underway and evaluation is expected to be made in the next period.

2.0 COLD TEST

The previous cold test work was successful in establishing that the dispersion curve of the circuit design was correct as far as could be determined prior to evaluation of the circuit on hot test. Most of the effort during the report period on cold test was devoted to to refining the circuit match for both the Type A and Type B circuits. Since our plan was to incorporate the Type A circuit into the first vehicle scheduled for hot test, the matching effort on that circuit was given priority.

A match design for the Type A circuit evolved early in the report period and was felt to be adequate for the hot test evaluation of the circuit over at least a portion of the operating band. A decision was made to commit that design to a hot test vehicle and to continue the match refinement for incorporation into the second hot test vehicle. The match obtained for the first hot test vehicle is shown in Figure 2. The match data in this figure show return loss in decibels as a function of frequency. The data are obtained by illuminating the input of the amplifier with the output of the amplifier terminated. The match is therefore one seen looking through the entire tube rather than the match of a single waveguide to circuit transition. As can be seen from Figure 2, the circuit match is good over the mid to low frequency range for the tube and deteriorates rapidly toward the high frequency end of its operating band. The match in Figure 2 is essentially that which is incorporated into the first SFD-237 hot test vehicle, serial No. G25H.

Further work on the Type A circuit match yielded a return loss curve shown in Figure 3. These data show an average return loss of approximately 15 db over more than 1000 MHz. This type of match characteristic is felt to be quite satisfactory and the design is expected to be incorporated into the second or third test vehicle.

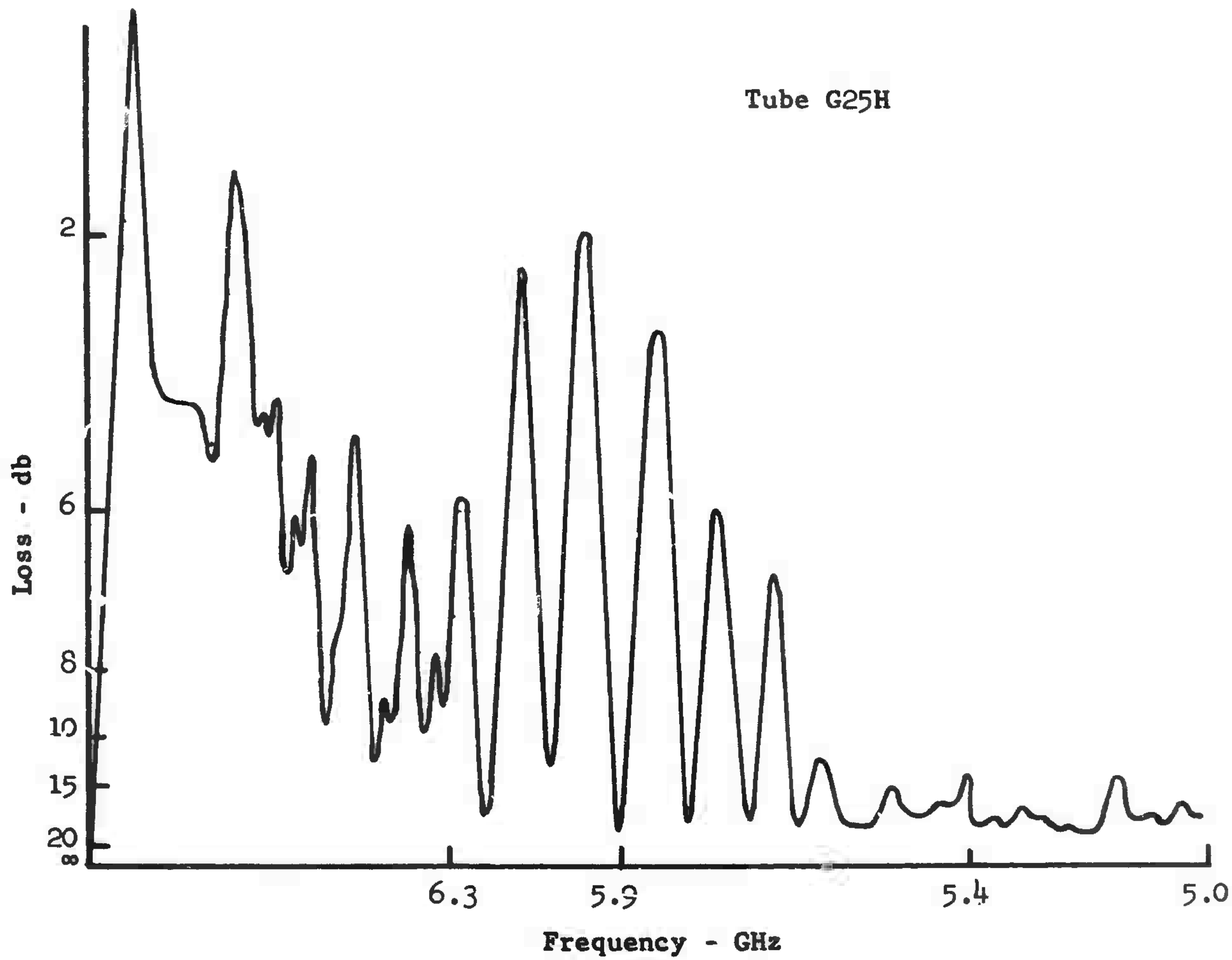

FIGURE 2 MATCH OBTAINED FOR FIRST HOT TEST VEHICLE, TUBE G25H

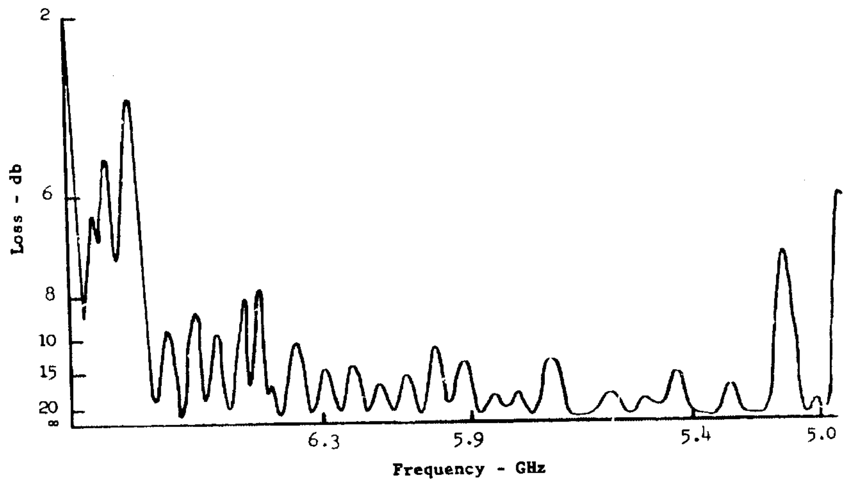

FIGURE 3 IMPROVED MATCH FOR USE IN SECOND HOT TEST VEHICLE

Sufficient work has been done during this period on the Type B circuit match to permit the work to progress to the construction of a hot test vehicle. Figures 4 and 5 show the waveguide to circuit transition matches for the input and output of the amplifier, respectively.

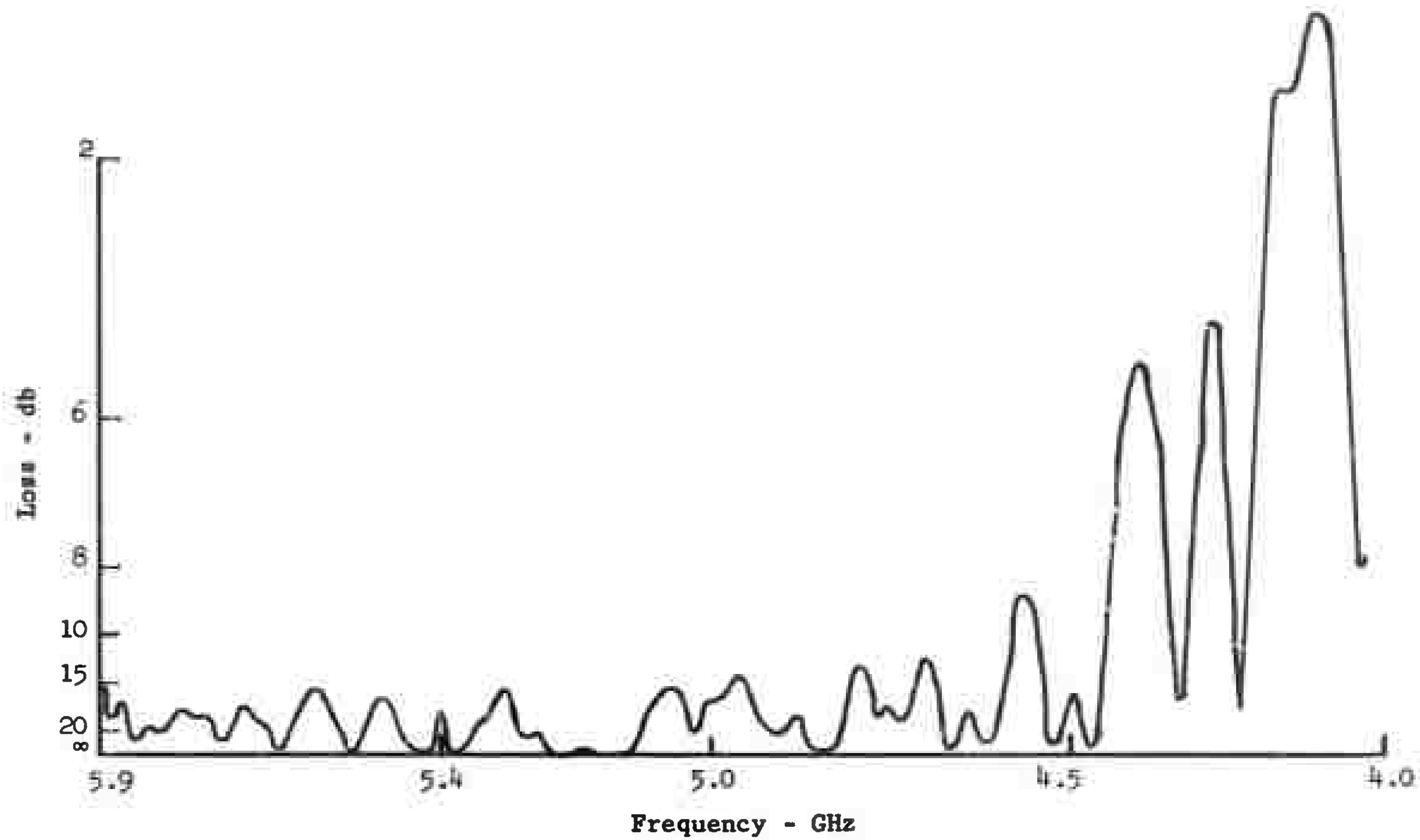

FIGURE 4 WAVEGUIDE TO CIRCUIT TRANSITION MATCH FOR AMPLIFIER INPUT

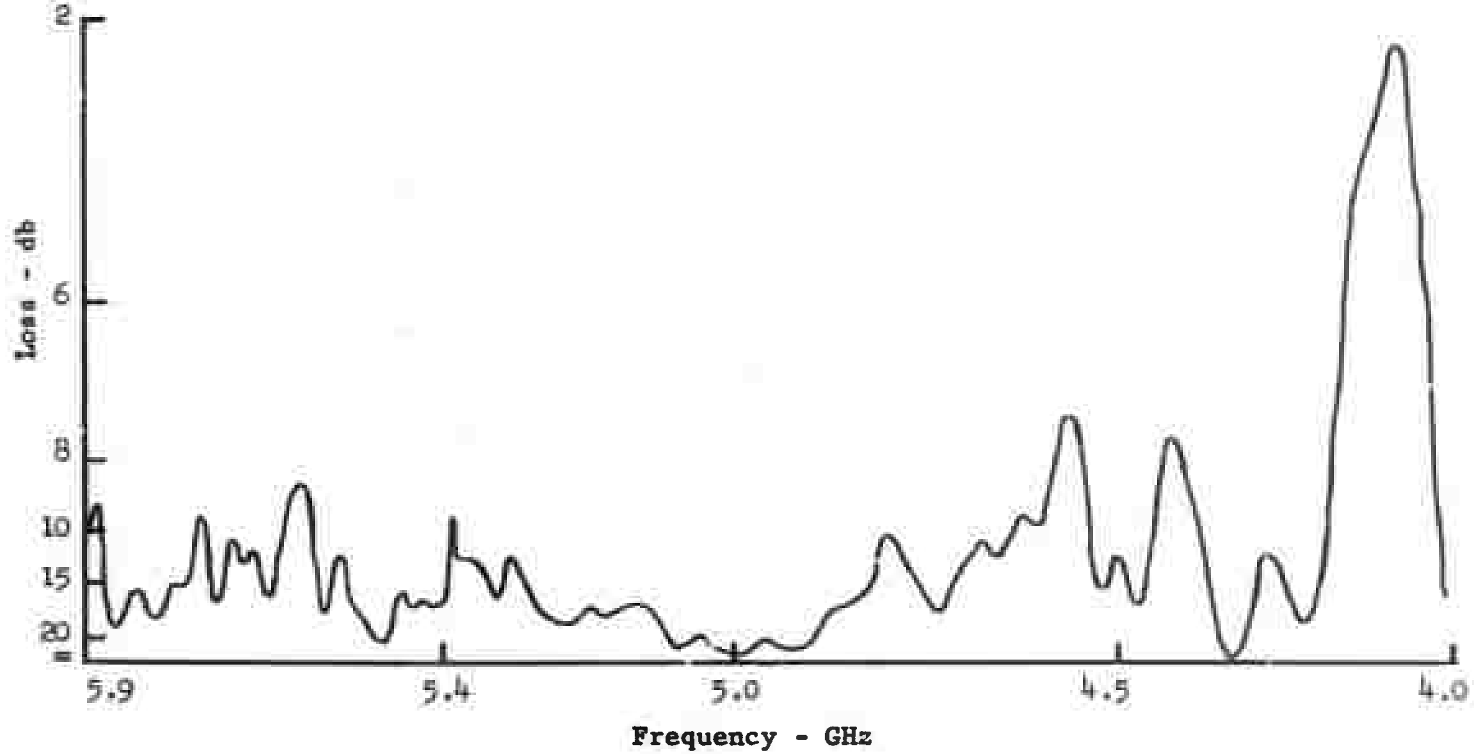

FIGURE 5 WAVEGUIDE TO CIRCUIT TRANSITION MATCH FOR AMPLIFIER OUTPUT

3.0 TUBE CONSTRUCTION

The first SFD-237 vehicle to undergo hot test was serial No. G25H. This tube was made with a mechanical design which, with one exception, will permit it to be used directly in the shielded permanent magnet assembly. The one exception is that the input and output waveguides are left emerging radially from the tube whereas in the final package design the waveguides will be bent along the cathode axis to emerge axially from the package. The mechanical design of G25H is therefore presently near its final form. The waveguides in their present form (emerging radially) permit the early test vehicles to fit two different test installations, one of which will later be modified to accept the test vehicles in either of the two waveguide arrangements.

The first test vehicle utilized a Type A slow wave circuit. Both anode and cathode assemblies were liquid cooled, as was the output ceramic window. No control electrode was employed since only pulse modulated tests were planned for this vehicle. All tests conducted on G25H used a line type pulsed modulator.

The first test showed that the tube drew current at a low voltage. This voltage was too low for the magnetic field intensity used and it was found to be caused by operation in a band edge oscillation. Efforts to obtain signal amplification were not successful because of the band edge oscillation and no other RF duty could be obtained.

The tube was rebuilt and was designated G25H-1. A change in the end hat geometry was made in an attempt to combat the band edge oscillation. No signal amplification could be obtained because of the band edge oscillation which was present but the effect of the change which was noticeable was that the amplifier would operate to higher peak current levels in the band edge before arcing out.

The amplifier was rebuilt again and was designated G25H-2. The design was modified to change the drift space geometry on the cathode sub-assembly in the area which would later be occupied by the control electrode in the design. For the first time, it was possible to observe signal amplification, but all data which could be obtained showed the output still to be heavily contaminated by band edge interference. The tube developed high internal gas pressure which was found not to be a leak but was suspected to be caused by the overheating of some part of the amplifier. For the levels of average power operation which had been encountered, the cathode sub-assembly was suspected.

The amplifier was rebuilt and designated G25H-3. The design was modified once more and the anode-cathode spacing was increased by 10%. This design change, coupled with the two others which had previously been made, had a significant effect on RF performance. For the first time, clean RF amplification was observed. The performance of this vehicle is shown in Figure 6. Amplification was obtained over approximately a 300 MHz band with constant applied pulse voltage of approximately 26 kv. Peak output power levels ranged from approximately 900 kw to 1.35 Mw. Efficiencies ranged from the mid-40's to the upper 50's. Operation at frequencies higher than 5.6 GHz was not possible because of the onset of band edge contamination. It was suspected that higher frequency performance would be automatically degraded by the poor match this circuit has at high frequencies. Below 5.6 GHz, however, the amplification is quite satisfactory. Data were obtained at a pulse length of 18 μsec and, in order to eliminate possible average power problems at this early stage, at a duty factor of 0.00045.

Tube G25H-3 once again developed a high internal gas pressure which was found not to be a leak. The tube was opened and it was confirmed that there was no leak; it was also examined and no physical damage was found. The tube was resealed and pumped as G25H-4. Before proceeding with RF operating tests, the vehicle was used to establish

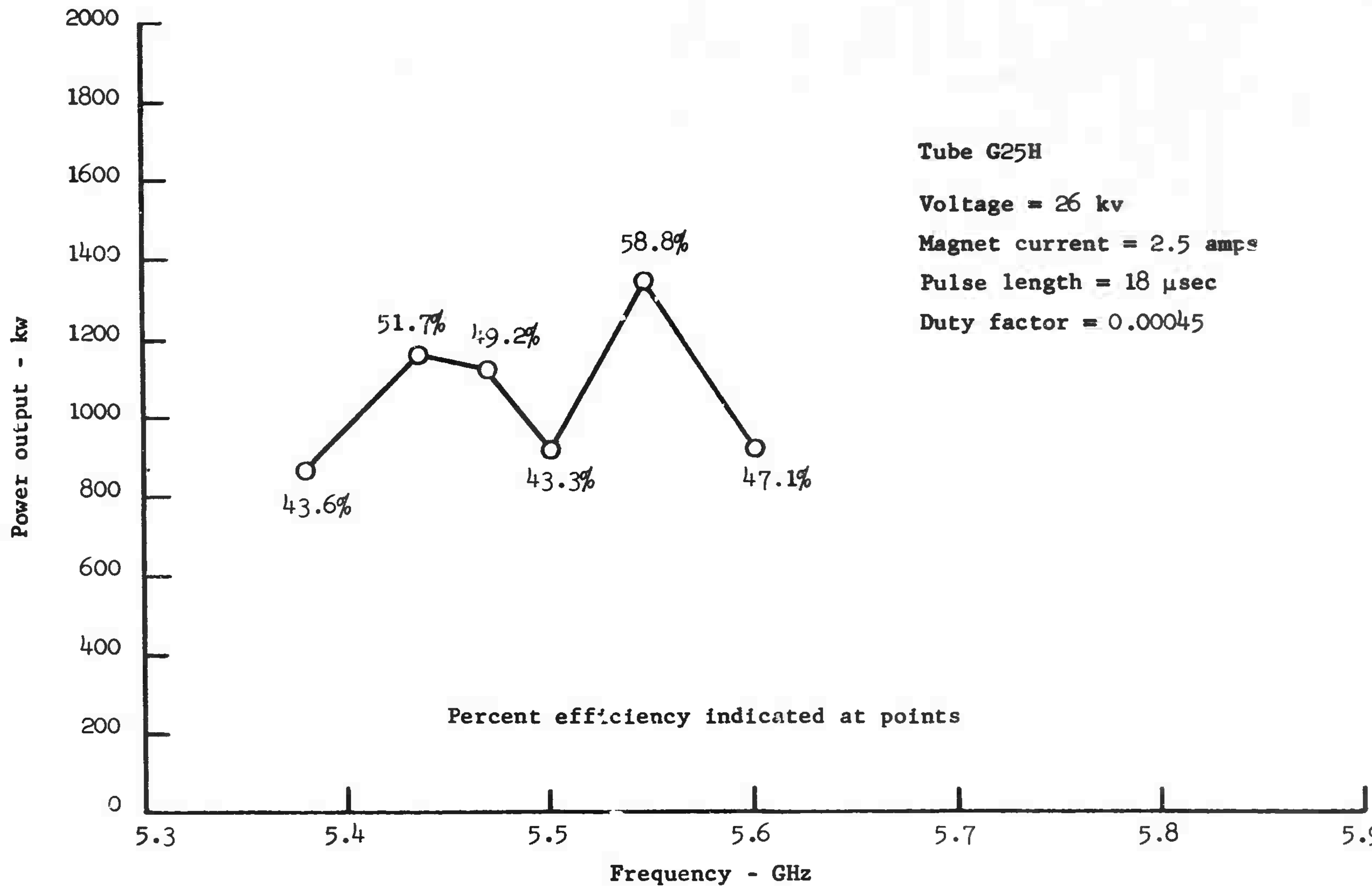

FIGURE 6 PERFORMANCE FOR TUBE G25H

the dc hold off properties of the structure being used. The vehicle was operated with full magnetic field and no RF drive power applied with voltages as high as 35 kv. After reaching that point, the tube was held in a non-operating condition at 32 kv for 30 minutes without arcing. This test was considered adequate to permit the present design to be used for the first control electrode test vehicle.

Tube G25H-4 was put on RF test again and data which were obtained confirmed the previously obtained data for tube G25H-3. High internal gas pressure, however, again developed and when the tube was opened for inspection, a cracked ceramic support was found on the cathode sub-assembly which indicated overheating.

The second test vehicle is under construction. This vehicle is to have a control electrode. It will have a Type A slow wave circuit incorporating the improved match shown in Figure 3. The second test vehicle was originally to have the same type of cathode and the same cathode geometry as was used in tubes G25H-3 and G25H-4, but the evidence of the thermal inadequacies of that design and certain problems associated with the fabrication of the sub-assembly dictated a change in the cathode design.

Several cathode assembly design changes are being carried out. These have to do mainly with the thermal capability of the structure. The control electrode portion of the sub-assembly has been designed so that it will function more reliably both electrically and mechanically. Improved coolant contact with both the cathode and the control electrode will account for most of the thermal capability increase of the new cathode design.

The original cathode assembly design was predicated on a desirable but not mandatory condition that cathode coolant does not contact any portion of the assembly at high potential. This resulted in a cathode design which relied upon the conduction of cathode dissipation power to the coolant through an insulating ceramic. This proved to be an undesirable and unnecessary complication. The amplifier, when contained in the system, will use a coolant which has a sufficiently high resistivity so that the packaged amplifier can be built as required with only two coolant connections, both of which will be at ground potential. The new cathode design therefore will be such that the coolant is in contact with high potential internally but provision will be made in the package design to incorporate the necessary insulating coolant column internal to the package.

The essential parts for eight tubes are on hand with minor exceptions such as certain cathode and control electrode parts and certain parts concerned with the matching section on the amplifier which may still be subject to some change. These parts are available with a relatively short delivery cycle.

4.0 CATHODE MATERIAL STUDIES

During the report period, the program for the study of cathode materials has been concluded with sufficient information to proceed with the hot test program on the dc operated amplifiers. Pulsed tests were conducted on the same test vehicle using two different cathode materials. The materials used were a tungsten matrix impregnated cathode and a pure tungsten matrix cathode. Shown in Figures 7 and 8 are the V-I curves for the impregnated cathode and the tungsten cathode, respectively. The V-I curve obtained for the impregnated cathode indicates that this cathode should have sufficient capability for the first hot tests. It has been felt that the evaluation of the cathode material will be relevant only when the material is evaluated in the vehicle in which it will be required to operate. A continuation of evaluations in the test vehicle selected for this sub-program was therefore felt to be of limited value. The cathode material studies would, of course, be resumed if tests on the program's dc operated amplifiers indicated any serious cathode deficiencies.

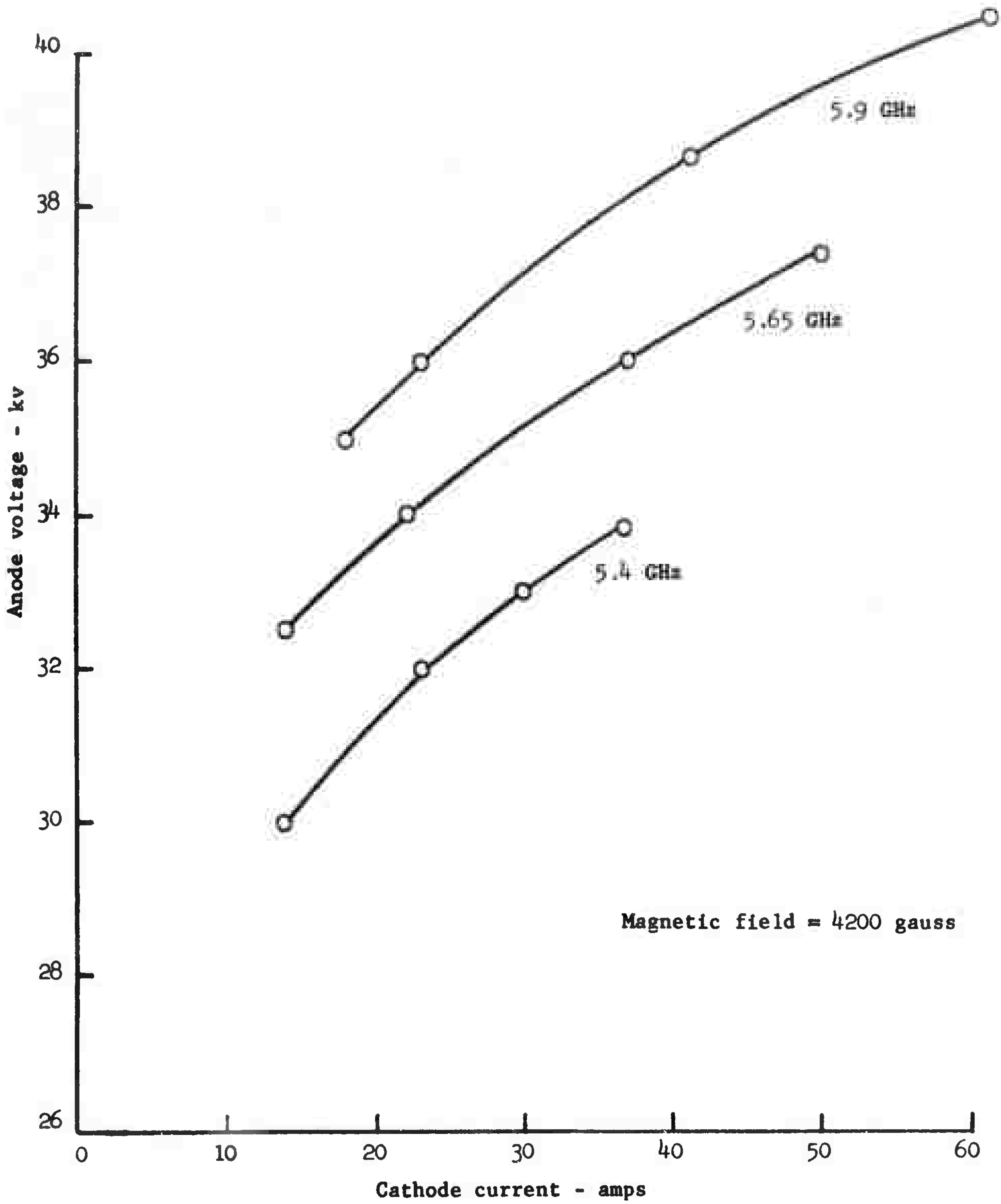

FIGURE 7 V-I CURVES FOR IMPREGNATED TUNGSTEN MATRIX CATHODE

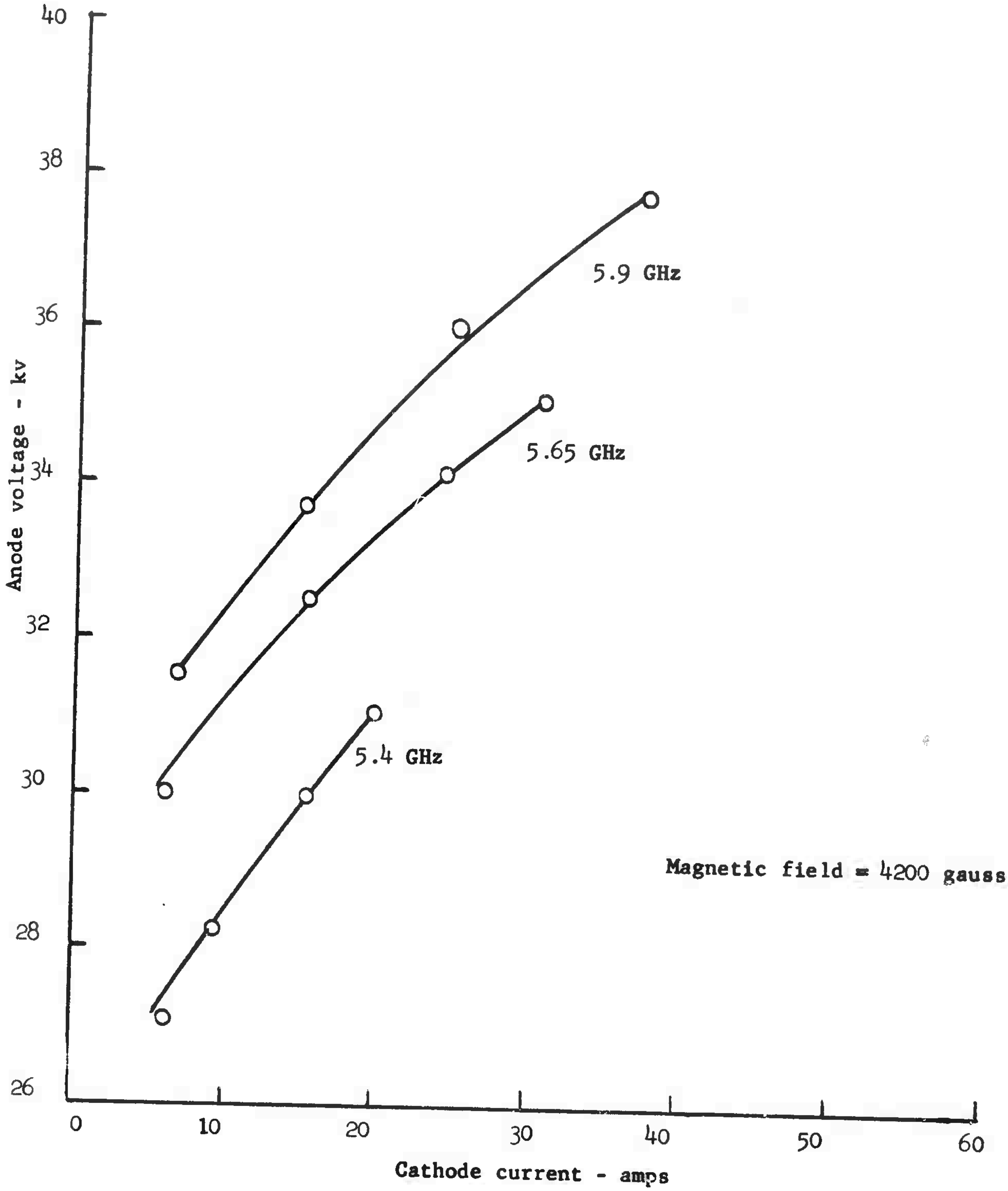

FIGURE 8 V-I CURVES FOR PURE TUNGSTEN MATRIX CATHODE

5.0 TEST EQUIPMENT

All components for the test set are on hand with the exception of one water load and the main high voltage dc power supply. The power supply is scheduled for delivery late in October. The water load is scheduled to arrive in the next few weeks.

The test set has not been completely assembled but the necessary equipment is on hand with which to assemble waveguide equipment not only for the measurement of the gross performance characteristics of the system but also for the measurement of phase and spurious output. The necessary RF drive source is available and has been used in the testing of G25H and the test vehicle used for cathode material studies.

Until such time as the high voltage dc power supply arrives, we have provided an interim power supply with the necessary voltage capability to operate the amplifier on direct current. The interim power supply has a current rating which will permit its use in demonstrating the dc operated amplifiers to more than half the program goal of average power.

6.0 MAGNETIC CIRCUIT

The program requires that the tube delivered be packaged in a 9" maximum diameter shielded structure. The basic package design is shown in Figure 9.

The magnets used in this type of configuration are cylindrical and abut the amplifier body itself on each side. The return path for the flux is provided by means of a soft iron shell which surrounds the entire assembly. The design of the magnet and shielding shell is such that leakage flux adjacent to the shielding shell is small enough to permit amplifiers to be operated adjacent to each other without causing mutual interference. Packages of this configuration were investigated under Contract AF 30(602)-3633. On that program a shielded package tube was operated successfully. A photograph of the tube is shown in Figure 10 as an illustration of what the present program will yield.

To evaluate various magnetic geometries, a magnetic cold tester has been designed. The magnetic material which is planned for the package is Alnico V-7. This magnetic material was chosen as one which has sufficient coercive force and flux density capability to drive the air gap required while at the same time will be quite readily available from more than one supplier. Alnico V-7 is material which has been used on our X-band program and magnets have been received for use on this C-band program.

The first test structure resulted in a package which was 9" in diameter and approximately 21" long. The particular magnets chosen were not adequate to provide the required flux density in the gap. A conference with an independent consultant with whom S-F-D laboratories has worked in the past showed that the inadequacy of the design lay in the cross-sectional area provided for the magnet. It was also determined that the amount of space between the magnet and the shielding shell which had been provided for clearance in order to avoid the shunting effect of the shell on the magnet was larger than necessary. A new

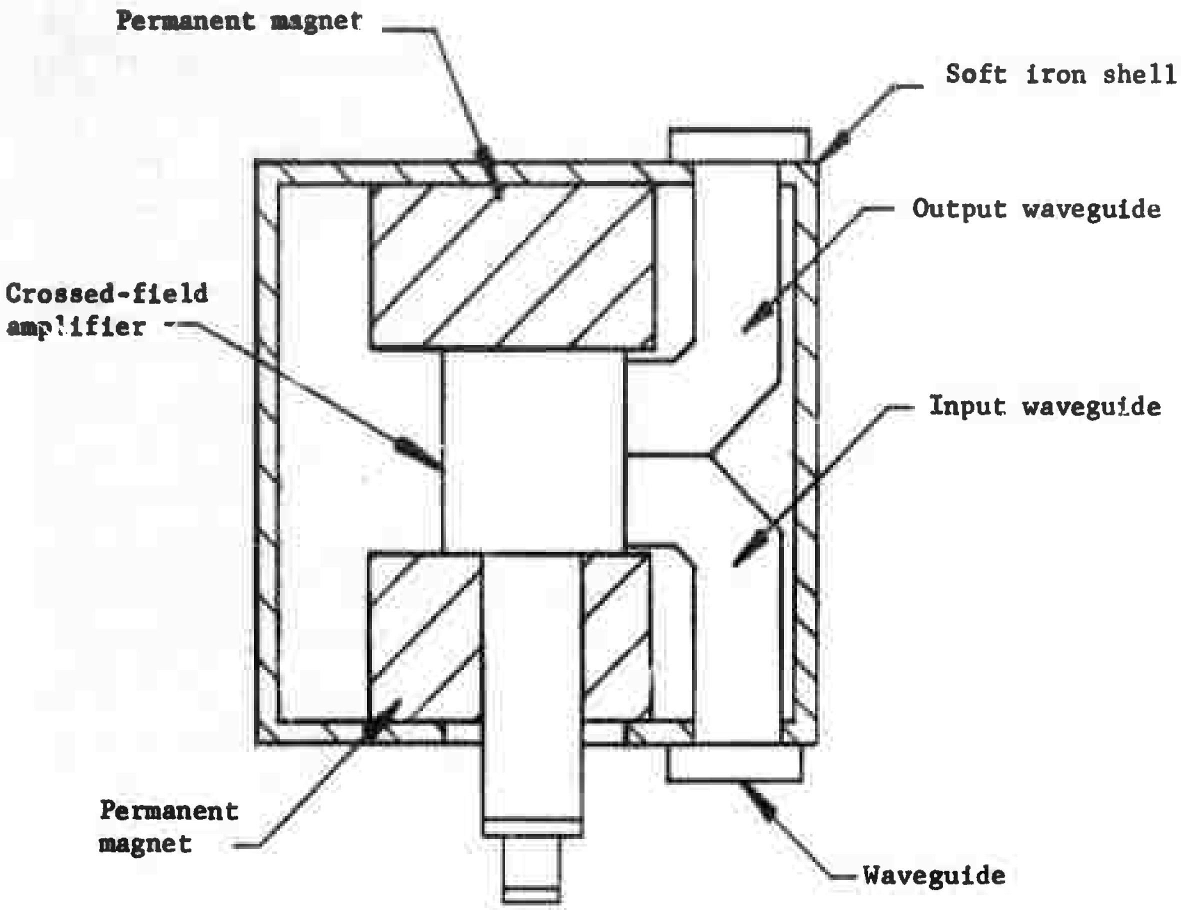

FIGURE 9 CUT-AWAY SKETCH OF SHIELDED CROSSED-FIELD AMPLIFIER PACKAGE

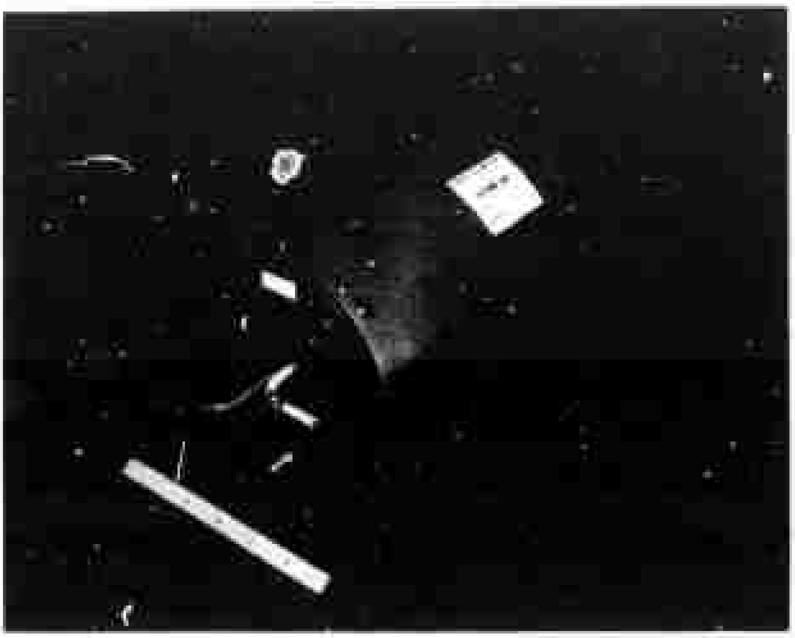

FIGURE 10 PHOTOGRAPH OF SHIELDED PACKAGE CROSSED-FIELD AMPLIFIER

design will be made in which the magnet diameter is increased to provide the area required and the clearance between the magnet and the shell will be decreased without detriment. It was also determined that the thickness of the shielding shell which had been selected was inadequate if external flux densities were to be kept at low levels. The thickness with which the test vehicle was constructed had been determined by the operation of the shell material at an internal flux density of 21 kilogauss. It was recommended by our consultant that this level be reduced to 14 kilogauss by providing greater cross-sectional area for the shell. The reduction to 14 kilogauss in the shell reduces the magnetomotive force drop of the shell to 10 oersteds.

The provision of a larger magnet area is being tested in an interim way by providing area on the inside diameter of the magnet rather than on the outside diameter (which is how the final design change will be made). An assembly having greater area has been made but has not yet been evaluated. No information obtained to date indicates that the package diameter of 9" cannot be met and no indication has been obtained that it will be necessary to go to exotic materials such as Alnico VIII or Alnico IX. Consideration of the use of materials such as platinum cobalt has not been made at all.

7.0 PROGRAM FOR NEXT QUARTER

1. Introduce control electrode into basic tube design.

2. Operate control electrode tube from a dc power supply and determine operating characteristics across frequency band at fixed voltage conditions.

3. Complete assembly of phase measuring equipment and begin calibration measurements.

4. Continue magnetic circuit design for 9" OD package.

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